Emission of single photons, hadrons, and dileptons in $Pb + Pb$ collisions at CERN SPS and quark hadron phase transition

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The production of single photons in $Pb + Pb$ collisions at the CERN SPS as measured by the WA98 experiment is analysed. A very good description of the data is obtained if a quark gluon plasma is assumed to be formed initially, which expands, cools, hadronizes, and undergoes freeze-out. A rich hadronic equation of state is used and the transverse expansion of the interacting system is taken into account. The recent estimates of photon production in quark-matter (at two loop level) along with the dominant reactions in the hadronic matter leading to photons are used. Most of the radiation of the photons is seen to arise from the quark-matter, which contributes dominantly through the mechanism of annihilation of quarks with scattering, and which in turn is possible only in a hot and dense plasma of quarks and gluons. The same treatment provides a very good description to hadronic spectra measured by several groups and the intermediate mass dileptons measured by the NA50 experiment, lending a strong support to the conclusion that quark gluon plasma has been formed in these collisions.

It has been recognised for a long time that electromagnetic radiations from relativistic heavy ion collisions would be a definitive signature of the formation of a hot and dense plasma of quarks and gluons, consequent to a quark-hadron phase transition. Once other signs of the quark-hadron transition, e.g., an enhanced production of strangeness, a suppression of J/ψ production, radiation of dileptons, etc., started to emerge, it was imperative that the more direct, yet much more difficult to isolate, signature of the hot and dense quark-gluon plasma, the single photons were identified. The WA98 experiment [1] has now reported observation of single photons in central $Pb + Pb$ collisions at the CERN SPS.

In the present work we show that these data, along with the hadronic spectra measured by several groups [2–4] and the intermediate mass dileptons measured by the NA50 [5] experiment are very well described if we assume that a quark-gluon plasma was formed in the collision.

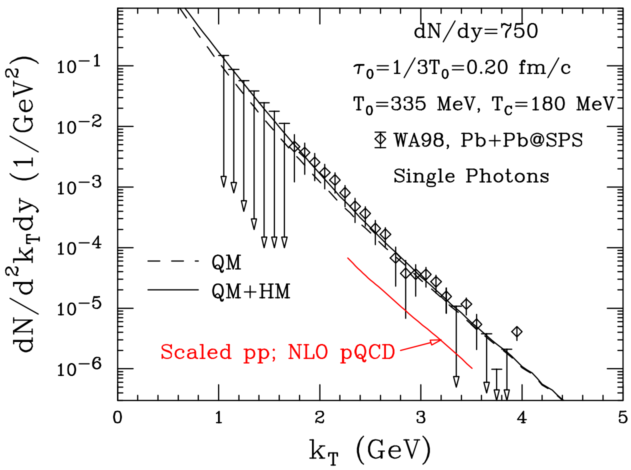

Figure 1. Single photon production in $Pb + Pb$ collision at the CERN SPS. QM stands for radiations from the quark matter in the QGP phase and the mixed phase, HM denotes the radiation from the hadronic matter in the mixed phase and the hadronic phase, and pQCD denotes the direct photons estimated by scaling the (NLO) perturbative quantum chromodynamics predictions.

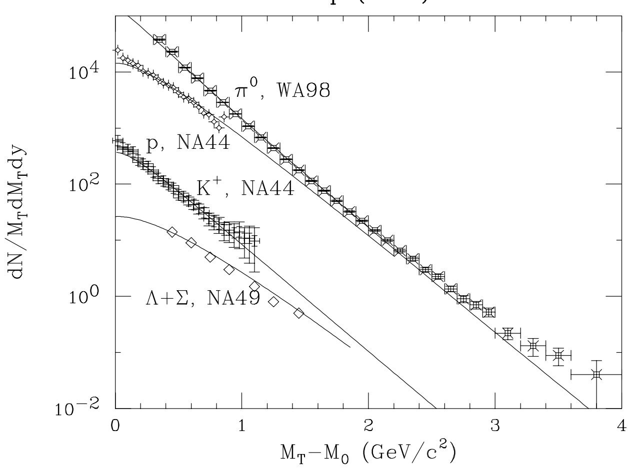

Figure 2. Transverse momentum spectra of neutral pions, protons, kaons and $\Sigma + \Lambda$ in central collisions of lead nuclei at CERN SPS. The initial conditions used for all the figures are identical.

A reanalysis of the WA80 data on single photons reported recently [6] incorporated two important developments which we utilize. Firstly, the hadronic equation of state is generalized to include all of the hadrons [7] in the particle data book. Secondly, we use the rate of single photon production from the quark matter to the order of two-loops reported recently by Aurenche et al [8]. This has two quite important results: (i) the dominance of the bremsstrahlung ($q\,q\,(g) \rightarrow q\,q\,(g)\,\gamma$) process for all momenta over the Compton ($q\,(\overline{q})\,g \rightarrow q\,(\overline{q})\,\gamma$) plus annihilation ($q\,\overline{q} \rightarrow g\,\gamma$) contributions included in the one-loop calculations available in the literature [9], and (ii) a very large contribution by a new mechanism which corresponds to the annihilation of a quark (scattered from a quark or a gluon) by an anti-quark. For analysis of the dilepton production we use the exhaustive rate calculations of Ref. [10]. We assume that a chemically and thermally equilibrated quark-gluon plasma is produced in such these collisions at the time τ_0, and use the isentropy condition [11];

$$\frac{2\pi^4}{45\zeta(3)}\frac{1}{A_T}\frac{dN}{dy} = 4aT_0^3\tau_0 \tag{1}$$

to estimate the initial temperature, where A_T is the transverse area. We have taken the average particle rapidity density as 750 for the 10% most central $Pb + Pb$ collisions at the CERN SPS energy as measured in the experiment. We use a mass number of 190 to account for non-zero impact parameter based on estimates of number of participants.

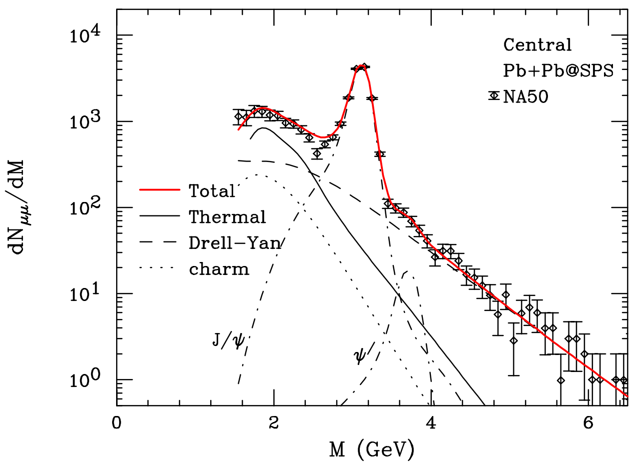

Figure 3. The invariant mass distribution of dilepton production in NA50 experiment [5].

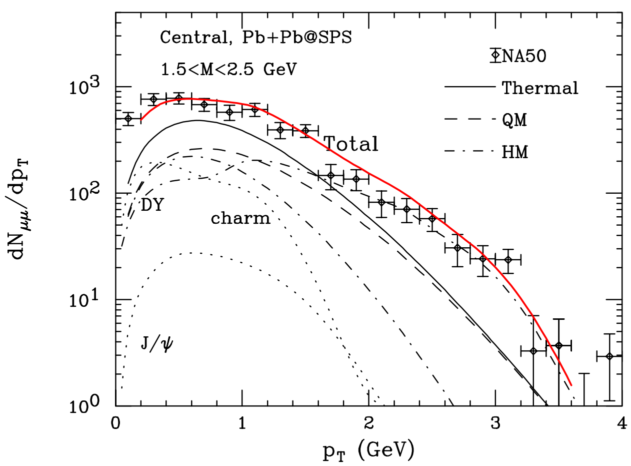

Figure 4. The p_T distribution of dileptons produced in central collision of lead nuclei.

The plasma is assumed to consist of massless quarks (u, d, and s) and gluons with the number of flavours as ≈ 2.5 to account for the mass of the strange quarks. We assume a rapid thermalization [12] so that the formation time is decided by the uncertainty relation and $\tau_0 = 1/3T_0$. The energy density profile is assumed to be proportional to the wounded nucleon distribution. We further assume that the phase transition takes place at $T = 180$ MeV and the freeze-out takes place at 120 MeV. The rates for the hadronic matter have been taken from Ref. [9] and the contribution of the A_1 resonance is included according to the suggestions of Xiong et al [13]. The relevant hydrodynamic equations are solved using the procedure [14] discussed earlier and an integration over history of evolution is performed [7].

In Fig. 1 we show our results for single photons. The dashed curve gives the contribution of the quark-matter and the solid curve gives the sum of the contributions of the quark matter and the hadronic matter. The NLO pQCD estimates for early hard photons scaled from the results for *pp* are also given. A very good description of the data is obtained. Consequences of variation of some of the parameters can be seen in Ref. [15]. The fit to pion spectra from the WA98 experiment [4], kaon and proton spectra from the NA44 experiment [2], and the $\Lambda + \Sigma$ spectra from the NA49 experiment [3] are given in Fig. 2. The production of intermediate mass dileptons measured by the NA50 experiment is shown in Fig. 3. We see that the sum of the thermal and Drell-Yan contributions provides a good description to the experimental data. We add that we have used the procedure described in Ref. [16] to simulate the detector acceptance. We also add that the thermal production is quite identical to the enhanced production of charm decay estimated by the NA50 group to 'explain' this excess. The corresponding fit to the p_T spectrum is shown in Fig. 4. It should be noted that contrary to the findings of Ref. [16] most of the radiations in the present work comes from the quark matter itself. This difference is most likely due to the rich equation of state along with a sophisticated evolution mechanism for the plasma employed in the present work [17].

In brief, we have shown that a single set of initial conditions, which involve a quark gluon plasma in the initial state and envisage a quark-hadron phase transition during the evolution, are able to provide a consistent description to single photons, dileptons, and hadrons produced in central $Pb+Pb$ collisions measured at the CERN SPS. This we feel, provides a very strong support to the claim that a quark gluon plasma is formed in these experiments.

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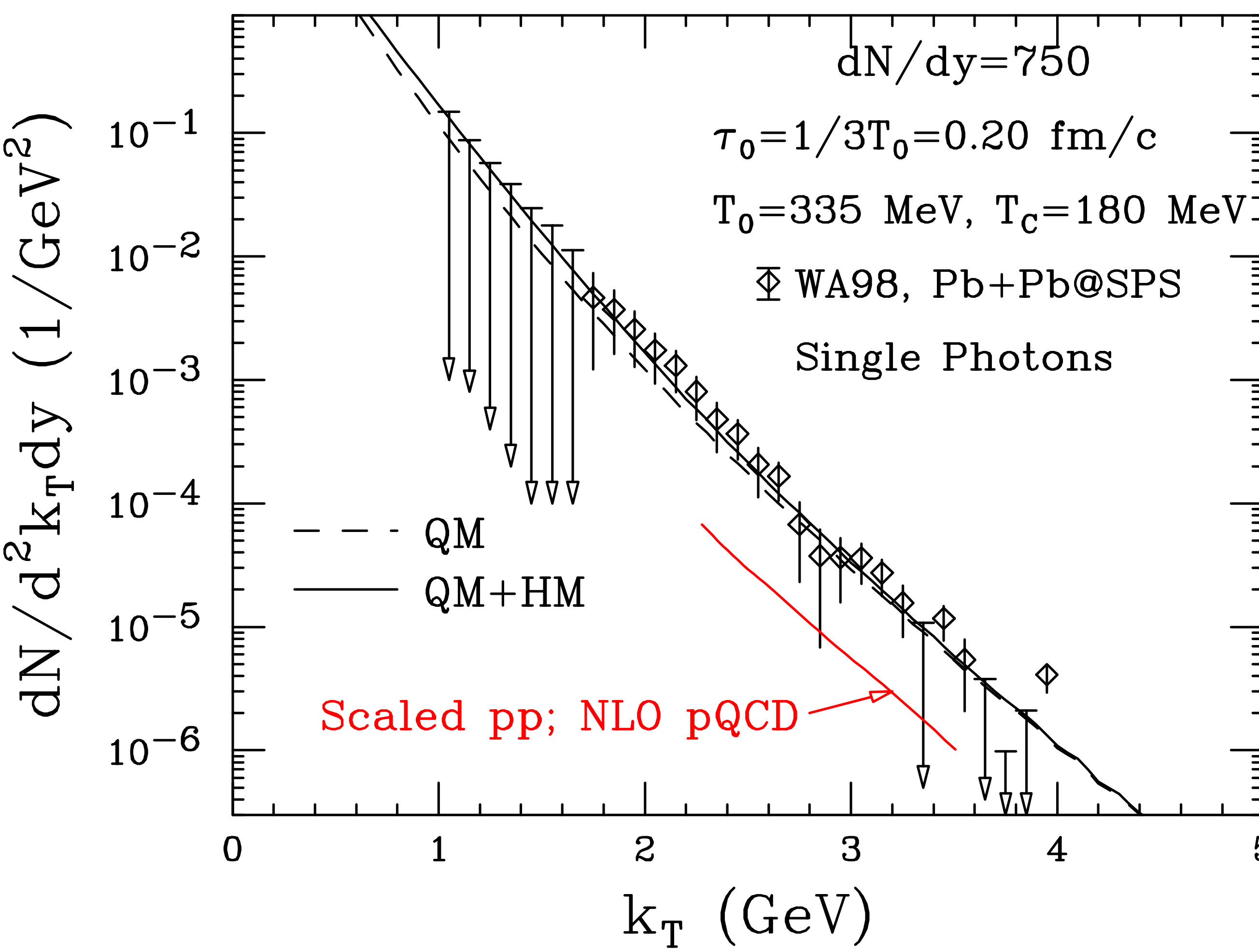
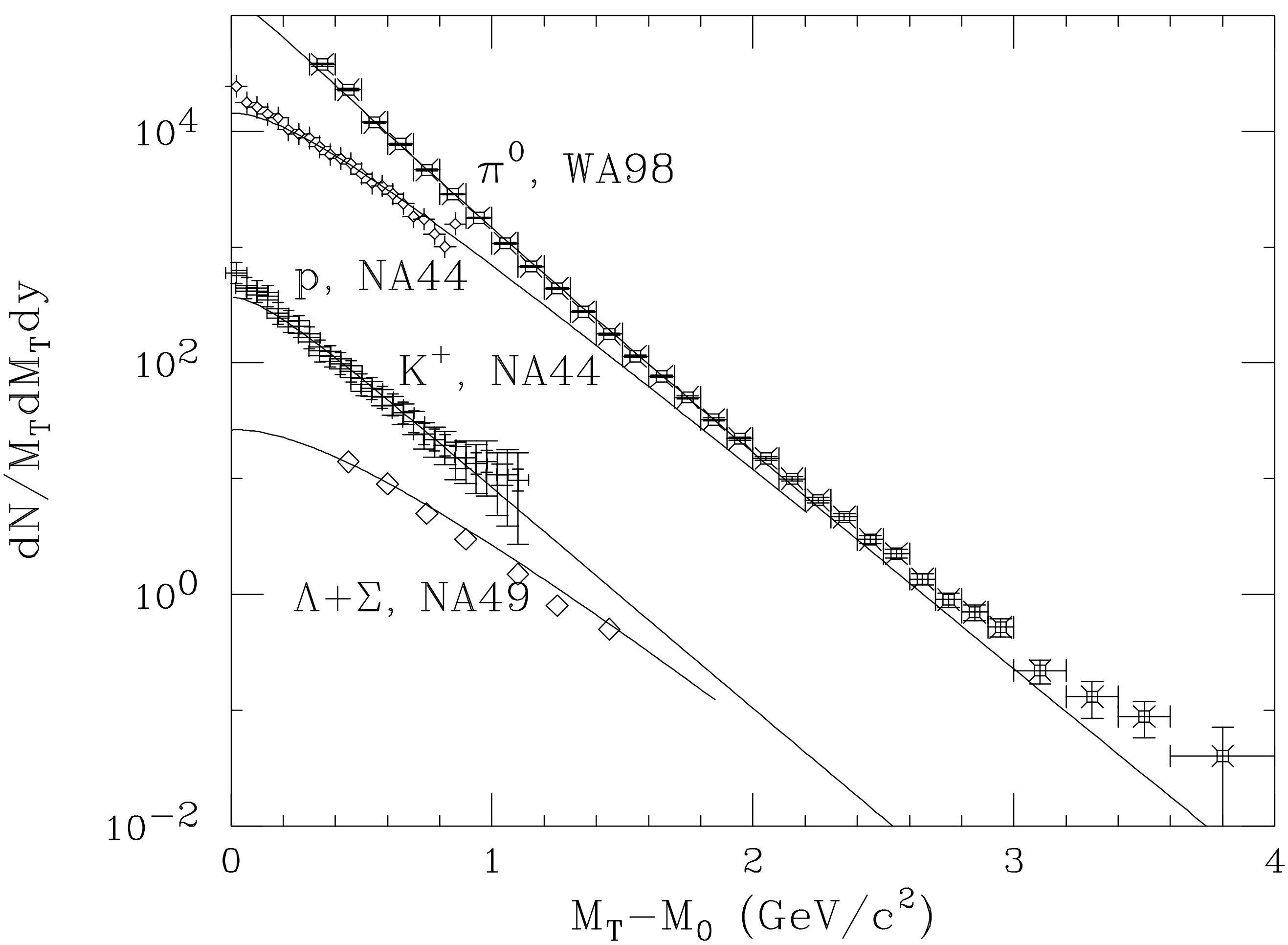
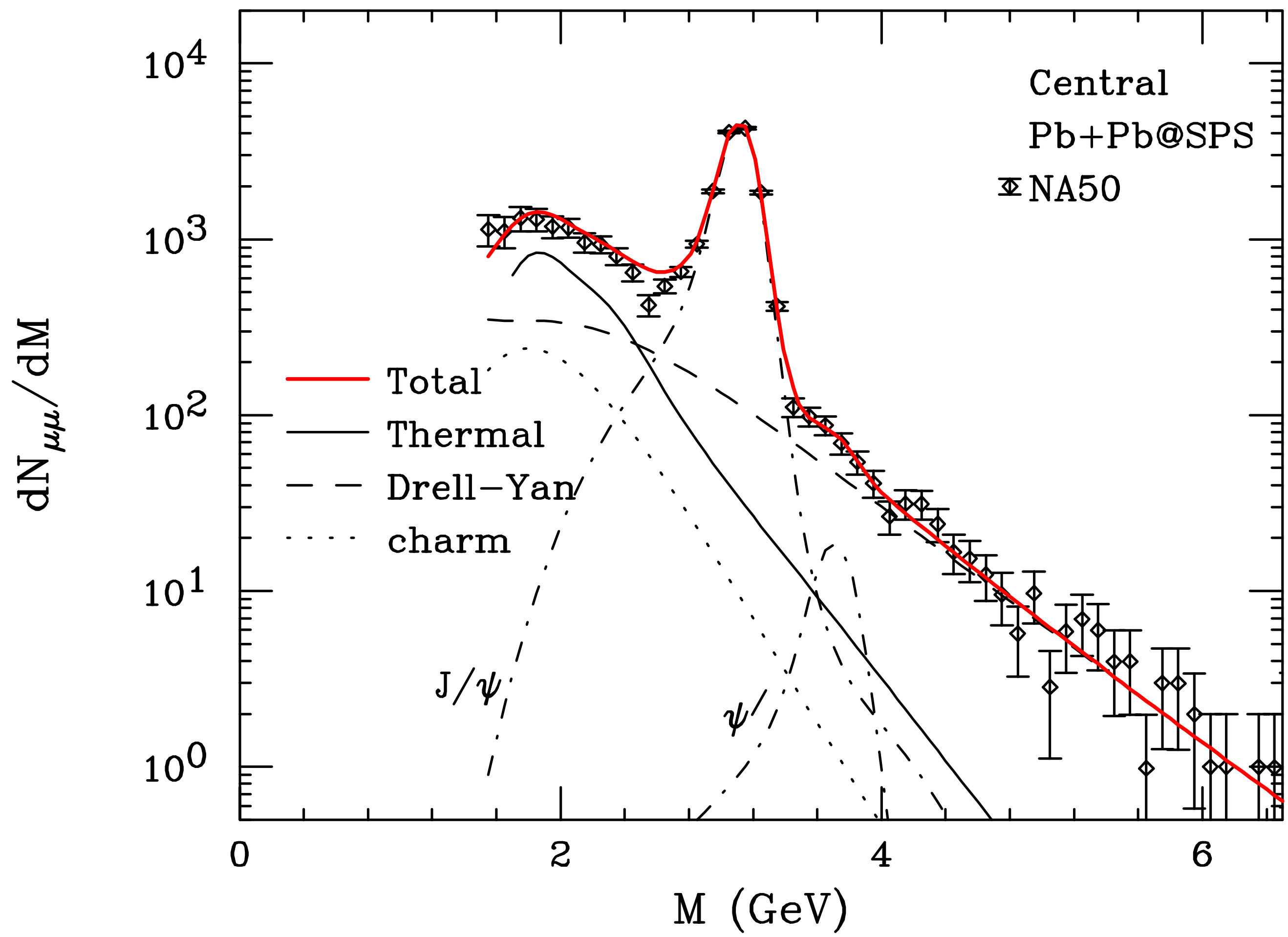


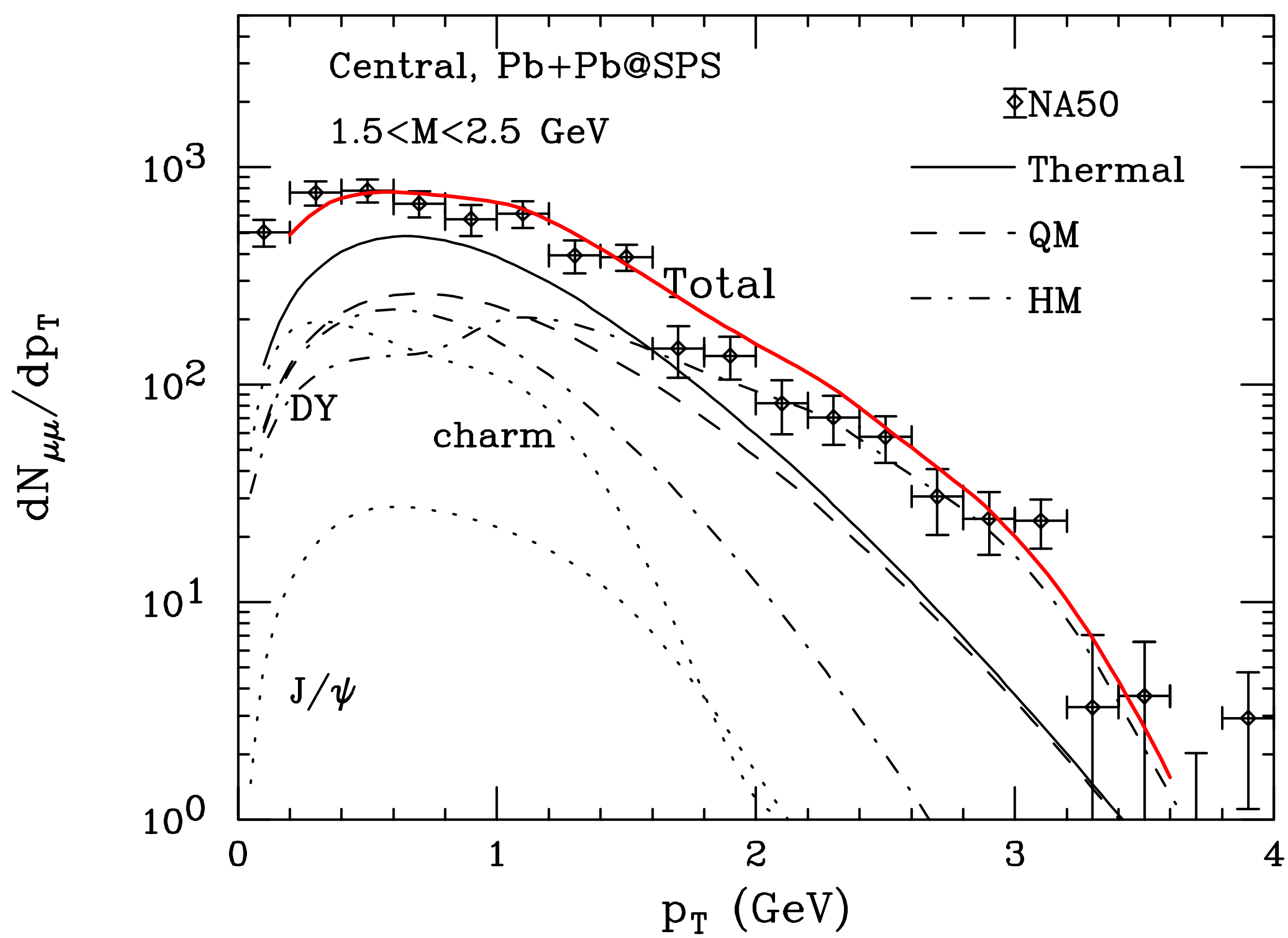
dN/dy=750
τ_0=1/3T_0=0.20 fm/c
T_0=335 MeV, T_C=180 MeV
WA98, Pb+Pb@SPS
Single Photons
QM
QM+HM
Scaled pp; NLO pQCD
dN/d^2k_Tdy (1/GeV^2)
k_T (GeV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
1
2
3
4
5



10^4
10^2
10^0
10^{-2}
0
1
2
3
4
$dN/M_T dM_T dy$
$M_T - M_0$ (GeV/c^2)
π^0, WA98
p, NA44
K^+, NA44
$\Lambda+\Sigma$, NA49



Central
Pb+Pb@SPS
NA50
Total
Thermal
Drell−Yan
charm
J/ψ
ψ'
$dN_{\mu\mu}/dM$
M (GeV)
10^4
10^3
10^2
10^1
10^0
0
2
4
6



Central, Pb+Pb@SPS
1.5<M<2.5 GeV
NA50
Thermal
QM
HM
Total
DY
charm
J/ψ
10^3
10^2
10^1
10^0
0
1
2
3
4
$dN_{\mu\mu}/dp_T$
p_T (GeV)